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# Lepton Flavor Violation at LEP II and Beyond

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## Abstract

If sleptons are produced at LEP II or the Next Linear Collider, lepton flavor violation can be probed at a level significantly below the current bounds from rare processes, such as $\mu \rightarrow e\gamma$. Polarizable $e^-$ beams and the $e^-e^-$ mode at the NLC are found to be powerful options.

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At present, two fundamental mysteries in particle physics are the origins of electroweak symmetry breaking and the fermion mass matrices. The experimental discovery of superpartners would represent enormous progress in our understanding of electroweak symmetry breaking, but would it also allow progress on the flavor problem? To date, nearly all experimental studies of supersymmetry have ignored the possibility of flavor mixings in the sfermion sector. However, since all superpartners must be given masses, all supersymmetric theories necessarily allow for the possibility of new flavor mixings beyond the standard model. In addition, there are now many supersymmetric theories of flavor, which predict a wide variety of superpartner flavor mixings. In this study, we examine the possibility of measuring these mixings at LEP II and the Next Linear Collider (NLC). Rare flavor changing processes, such as $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$, $b \to s\gamma$, and neutral meson mixing, already provide important constraints on the sfermion flavor mixings through the virtual effects of superpartners. However, as will be seen below, once superpartners are discovered, it will be possible to probe these mixings much more powerfully by directly observing the change in flavor occurring at the superpartner production and decay vertices. This talk is based on work done with N. Arkani-Hamed, H.-C. Cheng, and L. J. Hall [1].

In the minimal supersymmetric standard model, there are seven new flavor mixing matrices $W_a, a = u_{L,R}, d_{L,R}, e_{L,R}, \nu_L$, where, at the neutral gaugino vertex of species $a$, the generation $i$ scalar is converted to the generation $j$ fermion with amplitude $W_{aij}$. Clearly, if supersymmetry is correct, it will furnish a large new arena for studying the problem of flavor. In this study, we will concentrate on intergenerational mixing in the slepton sector. This choice is motivated by the theoretical prejudice that sleptons are lighter than squarks and so are presumably more likely to be seen at future colliders, and also by the absence of standard model lepton flavor violation, which implies that any flavor violation in the processes we consider is supersymmetric in origin. For simplicity, we specialize to the case of two generation mixing, and in particular, $\tilde{e}_R$–$\tilde{\mu}_R$ mixing. We define $\sin\theta_R \equiv W_{e_R 12}$, $\Delta m_R^2 \equiv m_{\tilde{e}_R}^2 - m_{\tilde{\mu}_R}^2$, and $m_R \equiv (m_{\tilde{e}_R} + m_{\tilde{\mu}_R})/2$. As in the case of neutrino oscillations, the power of various experiments is best displayed by plotting their reach in the $(\sin 2\theta_R, \Delta m_R^2)$

plane.

The most stringent current bound on $\tilde{e}_R$–$\tilde{\mu}_R$ mixing is from $B(\mu \to e\gamma) < 4.9 \times 10^{-11}$ [2]. If $\theta_R$ is comparable to the Cabibbo angle and $\Delta m_R^2 \sim m_R^2$, the rate for $\mu \to e\gamma$ is typically several orders of magnitude above the experimental bound. However, for nearly degenerate $\tilde{e}$ and $\tilde{\mu}$, the bound may be satisfied by a superGIM cancellation. For large $|\mu|$, two types of diagrams contribute to the process $\mu \to e\gamma$ [3]: one proportional to $\sin 2\theta_R \Delta m_R^2$, and one proportional to $\sin 2\theta_R \Delta m_R^2 \tilde{t}$, where $\tilde{t} = -(A + \mu \tan\beta)/m_R$. These two diagrams may interfere destructively, and the bound from $\mu \to e\gamma$ disappears for certain $\tilde{t}$. For $|\mu| \sim m_R, M_1$, an additional diagram weakens the bounds for large $\tilde{t}$ [4].

The flavor violating processes that we hope to observe at colliders are slepton pair production leading to $e^+e^- \to e^\pm\mu^\mp\tilde{\chi}^0\tilde{\chi}^0$ and $e^-e^- \to e^-\mu^-\tilde{\chi}^0\tilde{\chi}^0$, where for simplicity, we consider the case where the right-handed sleptons decay directly to the LSP. For large $\Delta m_R^2$, the flavor violating cross section is given simply by multiplying the flavor conserving cross sections by appropriate factors of the branching ratios $B(\tilde{e} \to \mu\tilde{\chi}^0) = B(\tilde{\mu} \to e\tilde{\chi}^0) = \frac{1}{2}\sin^2 2\theta_R$. However, when $\Delta m_R^2 < m_R\Gamma$, where $\Gamma$ is the slepton decay width, interference effects become important. For example, in the $e^-e^-$ case, where sleptons are produced only through $t$-channel neutralino exchange, the flavor violating cross section is given by replacing the branching ratios above with $\frac{1}{2}\sin^2 2\theta_R(\Delta m_R^2)^2/[(\Delta m_R^2)^2 + 4m_R^2\Gamma^2]$, which vanishes in the limit of degenerate sleptons, as it must. For $e^+e^-$, the flavor violating cross sections are more complicated, but have been properly included in this study. As seen above, $\Delta m_R^2$ is highly constrained by $\mu \to e\gamma$, and so the interference effect is important in much of the allowed parameter space and must be included if one is to assess the ability of future colliders to detect lepton flavor violation.

Having discussed the flavor violating cross sections, we now examine the possibility of detecting such flavor violating signals at future colliders. We first consider the sensitivity of the LEP II $e^+e^-$ collider, with a center of mass energy $\sqrt{s} = 190\,\mathrm{GeV}$ and an integrated luminosity of roughly $500\,\mathrm{pb}^{-1}$. To discuss the flavor violation discovery potential of LEP II, we must first choose some representative values for the various SUSY parameters. Sleptons

with mass below 85–90 GeV are expected to be discovered at LEP II. We therefore consider the case where $m_{\tilde{e}_R} \approx m_{\tilde{\mu}_R} \approx 80\,\mathrm{GeV}$. The LSP must be lighter than this, and we assume that the LSP is roughly Bino-like with mass $M_1 = 50$ GeV. These mass choices are representative of the parameter space available to LEP II, and lead to conclusions which are neither pessimistic nor optimistic. Implications of deviations from these choices are discussed in Ref. [1].

At LEP II energies, the dominant standard model background to the $e^\pm \mu^\mp \tilde{\chi}^0 \tilde{\chi}^0$ final state is $W$ pair production, where both $W$ bosons decay to $e$ or $\mu$, either directly or through $\tau$ leptons. Including branching ratios, this cross section is 680 fb. The $W^+W^-$ background may be reduced with cuts, as has been discussed in a number of studies [5]. Depending on the LSP mass, the cuts may be optimized to reduce the background to ∼10–100 fb, while retaining 40% – 60% of the signal. Given an integrated luminosity of $500\,\mathrm{pb}^{-1}$, the required cross section for a $5\sigma$ effect is ∼40–185 fb. The flavor violating cross section is plotted in Fig. 1, along with the constraint from $B(\mu \to e\gamma)$ for various values of $\tilde{t}$. The cross section contours extend to $\sin\theta_R \sim 0.15$, and, for low values of $\tilde{t}$, probe new regions of parameter space. Surprisingly, we find that LEP II, which produces merely a few hundred sleptons a year, may be able to detect lepton flavor violation.

If sleptons are not produced at LEP II, they may be discovered at the NLC. There are many options at the NLC, as both highly polarized $e^-$ beams and $e^+e^-$ and $e^-e^-$ modes may be available. We will assume the NLC design energy $\sqrt{s} = 500\,\mathrm{GeV}$ and luminosity $50\,(20)\,\mathrm{fb}^{-1}/\mathrm{yr}$ in $e^+e^-$ ($e^-e^-$) mode. For the NLC, we consider right-handed slepton masses $m_{\tilde{e}_R}$, $m_{\tilde{\mu}_R} \approx 200\,\mathrm{GeV}$, and $M_1 = 100\,\mathrm{GeV}$.

We consider first the $e^+e^-$ mode. At NLC energies, $W^+W^-$, $e^\pm \nu W^\mp$, and $(e^+e^-)W^+W^-$ all are significant backgrounds. Nevertheless, efficient cuts [6] and a right-polarized $e^-$ beam effectively isolate the flavor violating signal. Given a year's running at design luminosity, the required $5\sigma$ signal is 3.8 (3.6) fb for 90% (95%) right-handed beam polarization. The NLC in $e^+e^-$ mode is a powerful probe of the flavor violating parameter space, extending to $\sin\theta_R = 0.06$ and probing parameter space for which $B(\mu \to e\gamma) = 10^{-14}$ ($10^{-11}$) for $\tilde{t} = 2$

(50).

An intriguing feature of the NLC is its ability to run in $e^-e^-$ mode. Slepton pair production is allowed, as SUSY theories naturally provide Majorana particles, the neutralinos, which violate fermion number. However, many troublesome backgrounds, for example, $W$ pair production, are completely eliminated. In addition, this option allows one to polarize both beams. For RR beam polarization, there are essentially no backgrounds; the dominant background is $e^-\nu W^-$ [7], arising from imperfect beam polarization. With 90% (95%) right-polarized beams and without additional cuts, the required $5\sigma$ signal for one year's luminosity is 3.9 (2.5) fb. The reach in parameter space is shown in Fig. 2. This proves to be the most sensitive mode considered so far, probing mixing angles with $\sin\theta_R = 0.02$ and parameter space for which $B(\mu \to e\gamma) = 10^{-15}$ $(10^{-12})$ for $\tilde{t} = 2$ (50), far below the current bounds. We find that, if sleptons are kinematically accessible at the NLC, the $e\mu$ signal will provide either stringent upper bounds on slepton mixing or the exciting discovery of supersymmetric lepton flavor violation.

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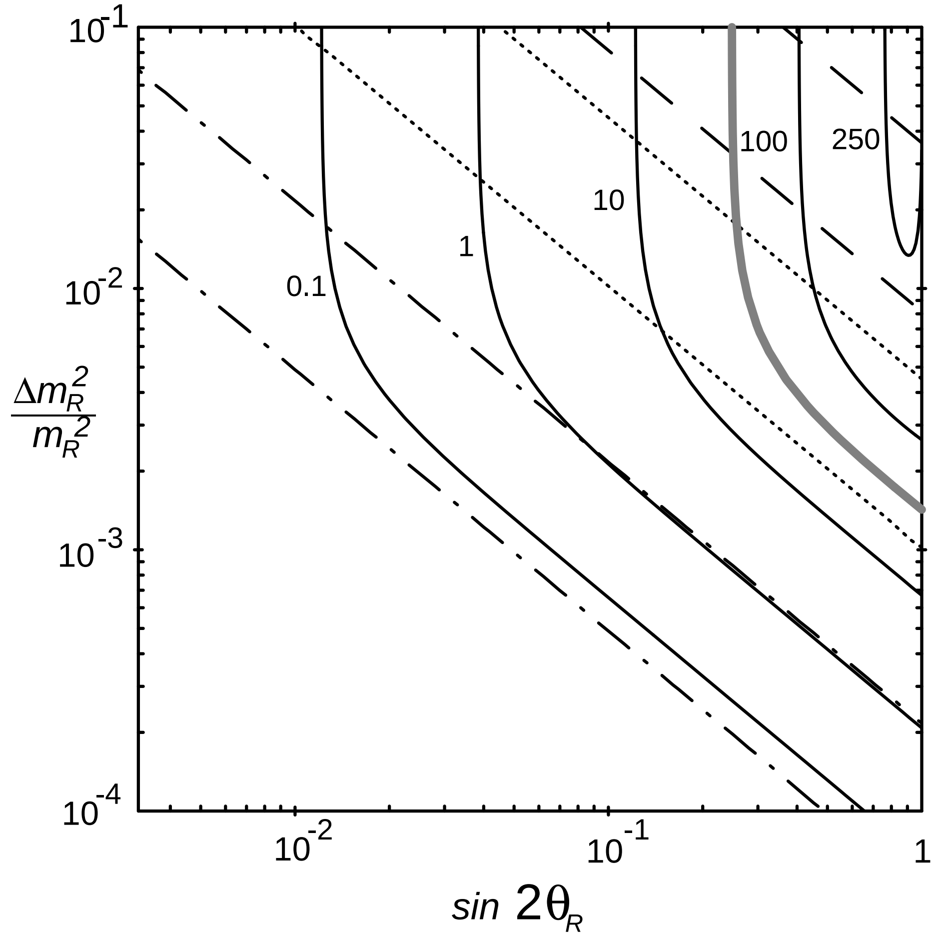


FIG. 1. Contours of constant $\sigma(e^+e^- \rightarrow e^\pm\mu^\mp\tilde{\chi}^0\tilde{\chi}^0)$ (solid) in fb for LEP II, with $\sqrt{s} = 190\,\mathrm{GeV}$, $m_{\tilde{e}_R}, m_{\tilde{\mu}_R} \approx 80\,\mathrm{GeV}$, and $M_1 = 50\,\mathrm{GeV}$. The thick gray contour represents the (optimal) experimental reach for one year's integrated luminosity. Constant contours of $B(\mu \rightarrow e\gamma) = 4.9 \times 10^{-11}$ and $2.5 \times 10^{-12}$ are also plotted for $\tilde{t} \equiv -(A + \mu \tan\beta)/\bar{m}_R = 0$ (dotted), 2 (dashed), and 50 (dot-dashed) and degenerate left-handed sleptons with mass 120 GeV.

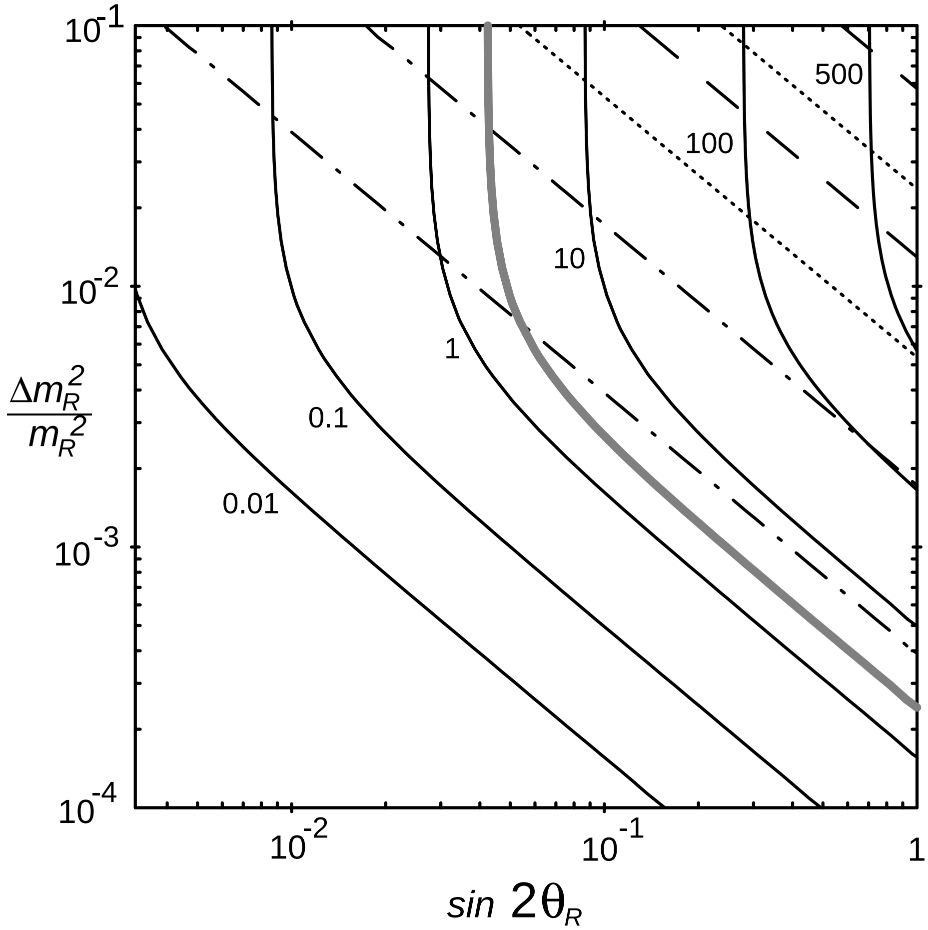


FIG. 2. Same as in Fig. 1, but for the NLC in $e_R^- e_R^-$ mode, with $\sqrt{s} = 500\,\mathrm{GeV}$, $m_{\tilde{e}_R}, m_{\tilde{\mu}_R} \approx 200\,\mathrm{GeV}$, $M_1 = 100\,\mathrm{GeV}$, and left-handed sleptons degenerate at 350 GeV.